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Research Note

$B_{\rm gg}$ revisited: The environments of low-excitation radio galaxies and unified models

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Abstract. Recent measurements of the galaxy clustering environments around intermediate-redshift radio sources have suggested a systematic environmental difference between radio galaxies and radio-loud quasars, in contradiction to the predictions of simple unified models for the two classes of object. I show that the apparent difference arises mainly as a result of the properties of low-excitation radio galaxies included in the radio-galaxy sample, which tend to lie in significantly richer environments. The environmental properties of high-excitation radio galaxies and quasars are statistically consistent in the redshift range $0.15 < z < 0.4$, as unified models would predict.

Key words. galaxies: active – galaxies: quasars: general – galaxies: clusters: general – radio continuum: galaxies

1. Introduction

In unified models for powerful radio galaxies and radio-loud quasars (Scheuer 1987, Barthel 1987, 1989) isotropic properties of the two classes of objects, such as their clustering environments, should be statistically identical. However, the classical unified models work best at high redshift (there are few low-redshift objects classified as radio-loud quasars) and at these redshifts the clustering environments of the sources are hard to measure. Some attempts have been made to test the predictions of unified models using X-ray observations of extended emission, assumed to be cluster-related (Hardcastle & Worrall 1999) but sample sizes are generally small and *ROSAT*-based work is generally not reliable because of the contamination of the X-ray emission by AGN- and radio-source-related components. *Chandra* should provide significantly better constraints from the X-ray once sufficient objects are in the archive, though it will be important to take into account the significant evolution undergone by the ICM of a radio-source host cluster between $z \sim 1$ and 0. In the meantime, there is still an important rôle for the traditional method of calculating the amplitude of the galaxy-galaxy or quasar-galaxy spatial covariance function, hereafter referred to as $B_{\rm gg}$ (e.g. Longair & Seldner 1979; Yee & Green 1987; Prestage & Peacock 1988; Yates, Miller & Peacock 1989; Ellingson, Yee & Green 1991; Hill & Lilly 1991; Yee & Ellingson 1993). Although it is recognised that selection in more than one optical filter is desirable to achive good statistics at high redshifts (Barr et al. 2003), at lower redshifts simple $B_{\rm gg}$ determinations seem likely to be able to provide a statistical measure of the environments of different classes of source.

Recently Harvanek et al. (2001: hereafter HESR) have carried out a large systematic study of the clustering properties of 3CR (Spinrad et al. 1985) radio sources. By making new observations, and collating and cross-calibrating data from the literature, they were able to obtain a nearly complete set of $B_{\rm gg}$ values in the redshift range $0.15 < z < 0.65$. 3CR objects in this redshift range are almost all luminous FRII-type radio galaxies or lobe- or core-dominated quasars. Yee & Green (1987) had shown that few low-redshift, radio-loud quasars are located in rich environments. HESR aimed to test the unified-model prediction that radio galaxies at these redshifts would also tend to lie in poor environments. They obtained the surprising result that the $B_{\rm gg}$ values of their 3CR radio galaxies were not consistent with those of a sample of radio-loud quasars compiled by Yee & Ellingson (1993: hereafter YE93) in the redshift range $0.15 < z < 0.4$, in the sense that a number of the radio galaxies were found in significantly richer environments than any quasar. An immediate objection to this result is that the YE93 quasars were not in general as radio-luminous in extended emission as the 3CR comparison sample (otherwise they would all have been 3CR objects themselves on the basis of their low-frequency extended emission, whereas only a fraction of them are in fact in 3CR). The effects of this bias are

hard to quantify, but since (for equal jet powers and source ages) simple radio-galaxy physics suggests that a more luminous object will lie in a richer environment, it might tend to produce a difference in the sense of the one observed by HESR. In what follows I shall ignore this potential problem and concentrate instead on the effects on HESR's conclusions of using a more sophisticated variant of the unified model.

2. Unification at low redshifts and the low-excitation objects

At low redshifts (or, more generally, low luminosities) the simple unified model of Barthel (1989) breaks down, most obviously because of the absence of low-redshift FRII quasars. I have argued elsewhere (Hardcastle et al. 1998) that the broad-line radio galaxies (BLRG) take the place of quasars at low redshifts/luminosities, although that does not rule out the possibility that more luminous BLRG are objects intermediate in viewing angle between quasars and narrow-line radio galaxies (NLRG) (e.g. Dennett-Thorpe et al. 2000). However, low-excitation radio galaxies (LERG) (Hine & Longair 1979; Laing et al. 1994), which are a significant population at low FRII luminosities, cannot be unified with either BLRG or quasars if the narrow-line emission is isotropic. Instead, it has been suggested (Barthel 1994, Laing et al. 1994), that they form a separate population, possibly unified at small angles to the line of sight with FRII-like BL Lac objects. They have other anomalous properties: Hardcastle et al. (1998) noted that the LERG in their $z < 0.3$ 3CR/3CRR sample were on average significantly smaller than the high-excitation objects, and that they included a number of objects with prominent jets and relaxed or absent hotspot structure. Hardcastle & Worrall (1999) found that the LERG in their *ROSAT*-observed subsample of 3CRR tended to have relatively luminous X-ray environments, whereas at least some of the NLRG at similar redshifts were in poorer environments. This motivates a re-analysis of the results of HESR taking into account the emission-line type of the radio galaxies.

3. Data and analysis

The data for 3CR objects, including the emission-line classifications, are taken from HESR, with emission-line classifications supplemented by data from the literature (Table 1). HESR took most of their emission-line classifications from Jackson & Rawlings (1997). Lacking new spectroscopic observations, I have classified objects that were not classified in Jackson & Rawlings mostly on the basis of qualitative statements in the literature, such as whether they show 'strong' or 'weak' emission lines and what species are present in the spectrum. These classifications must be regarded as best guesses only, but, as discussed by Hardcastle et al. (1998), the approach tends to give the same results as a more quantitative determination. To check this quantitatively, I examined all galax-

Table 1. Supplementary emission-line classifications for HESR sources

Source	Emission line classification in HESR	adopted	Reference
3C 28	–	E	1
3C 48	–	B	2
3C 49	–	N	3
3C 67	–	B	4
3C 93.1	–	N	3
3C 99	–	N	3
3C 196.1	–	N	3
3C 234	N/B?	N	5
3C 268.3	–	B?	9
3C 277.1	–	B	6
3C 288	–	E	7
3C 295	–	N	8
3C 299	–	N	3
3C 303.1	–	N	3
3C 346	–	E	3
3C 455	–	B	6

Emission-line types here are E (low-excitation), N (high-excitation, narrow-line) and B (broad-line). References are as follows: (1) Schmidt (1965) (2) Greenstein & Schmidt (1964) (3) Spinrad et al. (1985) (4) Laing et al. (1994) (5) See Hardcastle et al. (1997) for the argument for assigning this to the N class (6) Quasar, assumed broad-line (7) Smith & Spinrad (1980) (8) Minkowski (1960) (9) Laing & Riley, in preparation.

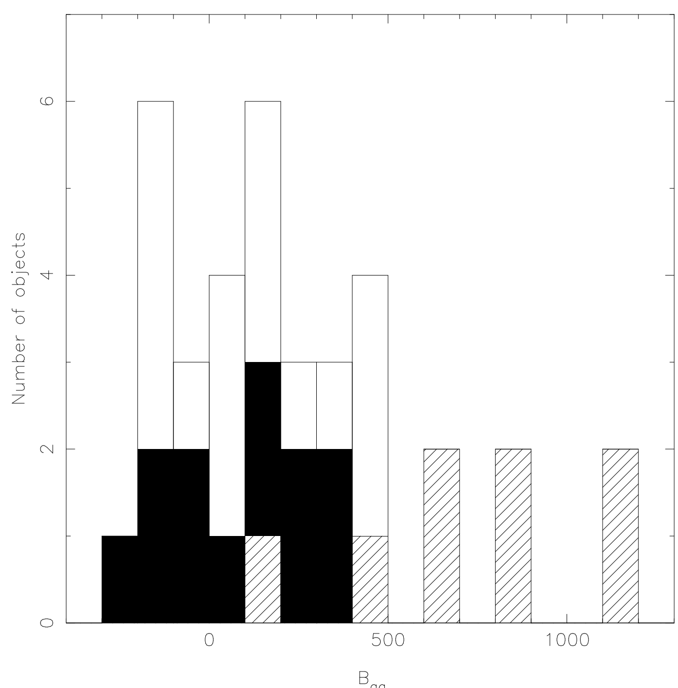

Fig. 1. Histogram of B_{gg} values for the $0.15 < z < 0.4$ objects from the HESR 3CR sample. Empty boxes indicate narrow-line objects, filled boxes broad-line objects (including quasars) and hatched boxes low-excitation objects.

ies that are classified both in Jackson & Rawlings and in Spinrad et al. (1985), comparing Spinrad et al.'s qualitative spectral classification with the Jackson & Rawlings class. The two papers were taken to agree if an object classed as Spinrad et al. as 'WE' or 'ABS' was classed by Jackson & Rawlings as a low-excitation object, or if an object classed by Spinrad et al. as 'SE' was classed by Jackson & Rawlings as a high-excitation object or 'weak quasar' (effectively a broad-line radio galaxy). Of the 97 overlapping objects, the two papers disagreed on only 8. This gives us some confidence that a qualitative approach will produce acceptable results. One object, 3C 142.1, remains unclassified, but lies outside the redshift range of particular interest in any case. Following HESR, 3C 275 and 3C 435A were omitted from the analysis. The data for HESR's comparison sample of radio-loud quasars were taken directly from YE93; HESR's B_{gg} values were taken in preference to YE93's where the sample had objects in common.

Fig. 1 shows the distribution of B_{gg} values for the objects in the 3CR sample with $0.15 < z < 0.4$, classified by emission-line properties. This may be compared with the left-hand panel of HESR's figure 6. It is clear that the low-excitation objects have a different distribution of B_{gg} from the high-excitation radio galaxies and quasars; in fact, all the 3CR objects in the richest environments found by HESR are LERG.

HESR used a Kolmogorov-Smirnov test to investigate the differences in B_{gg} distribution between the radio galaxies and quasars in their sample with $0.15 < z < 0.4$. To compare with HESR's approach, I use a quasar sample consisting of 21 YE93 quasars (the 24 objects in the redshift range, omitting the 3 quasars in the HESR 3CR sample) plus the 5 quasars from the 3CR sample, giving 26 quasars in all. In the HESR redshift range there are 31 radio galaxies (including BLRG and N-galaxies; here I class these with the NLRG for consistency with HESR). The K-S test finds only a 5% probability that these two samples are drawn from the same parent distribution, consistent with HESR's value of 3%. But if the 8 LERG are excluded from the radio galaxy sample, the K-S probability that the two are from the same parent population rises to 50%; there is no significant difference between the distributions of radio galaxies and quasars in these samples in this redshift range.

We can restrict ourselves to the 3CR-derived sample with $0.15 < z < 0.4$ in order to test unified models without including the lower-radio-power YE93 quasars. Here, in order to obtain a sufficiently large sample of sources that make a small angle to the line of sight to apply statistical tests, I include the BLRG with the quasars; this is a valid procedure whether or not some of the BLRG are intermediate-angle objects. In this sample, the B_{gg} distribution of the 12 broad-line objects (quasars and BLRG) has only a 5% probability of being drawn from the same population as the 24 LERG and NLRG combined (cf. Fig. 1), but a 72% probability of being drawn from the same population as the 16 NLRG; thus, if we neglect the difference between LERG and NLRG, there is a problem for low-redshift unification as described by Hardcastle et al. (1998), while if we remove the LERG there is no problem. On the other hand, the B_{gg} distribution of the LERG with $0.15 < z < 0.4$ has a 0.04% probability of being drawn from the same population as the other 3CR objects, a highly significant result. To summarize, all the differences between the distributions of radio galaxies and quasars/broad-line objects in the redshift range $0.15 < z < 0.4$ become statistically insignificant if the LERG are excluded from the radio galaxy sample; the LERG have significantly different properties from the other objects.

4. Discussion and conclusions

The key result of this work is that 3CR LERG lie in significantly richer environments than the HERG/quasar population at comparable redshifts. This strong difference between the environmental properties of LERG and HERG supports suggestions by Hardcastle et al. (1998) and Hardcastle & Worrall (1999) that the 3CR LERG population is physically different from the HERG. If we believe that the emission-line properties of the radio source reflect the power of the jet (e.g. Rawlings & Saunders 1991) then a plausible explanation is that at least some LERG are intrinsically low-jet-power radio galaxies which owe their comparatively high overall radio luminosity and their other properties (small size, dissipative jets, relaxed appearance – cf. Hardcastle et al. 1998, Harvanek & Stocke 2002) to a rich environment. This recalls, and may be related to, the arguments of Barthel & Arnaud (1996).

The fact that the narrow-line objects and quasars have similar B_{gg} distributions, when the LERG are excluded, supports the version of the orientation-based unified model for radio galaxies and quasars outlined in section 2.

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